Evaluation of the Magnetic Field Generated by the Inverter of an Electric Vehicle

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In hybrid and electric vehicles, passengers sit very close to an electric system of significant power, which means that they may be subjected to high electromagnetic fields. The hazards of long-term exposure to these fields must be taken into account when designing electric vehicles and their components. Among all the electric devices present in the power train, the electronic converter is the most difficult to analyze, given that it works with different frequencies. In this paper, a methodology to evaluate the magnetic field created by a power electronics converter is proposed. After a brief overview of the recommendations of electromagnetic fields exposure, the magnetic field produced by an inverter is analyzed using finite element techniques. The results obtained are compared to laboratory measurements, taken from a real inverter, in order to validate the model. Finally, results are used to draw some conclusions regarding vehicle design criteria and magnetic shielding efficiency.

***Index Terms*—AC-DC power converters, electric vehicles, magnetic field measurement, magnetic shielding, modeling, occupational safety.**

I. Introduction

THE effects of electromagnetic fields (EMFs) on the human body have been studied for more than 20 years [1]. During that period, several studies have tried to prove the relationship between a long-term exposure to electromagnetic fields and different pathologies (cancer, leukemia, etc.), without finding evidence for it. Biological effects caused by acute exposure to high EMFs levels, which are explained by recognized biophysical mechanisms, have been scientifically proved [2]. External AC magnetic fields induce electric fields and currents in the body, which, for very high field strengths, cause nerve and muscle stimulation and changes in the central nervous system [3]. These short-term effects on the body appear only under very strong fields. But the consequences of the long-term exposure to lower EMFs are more difficult to evaluate. Since it is impossible to prove that there is no relationship between several illnesses and a lengthy exposure to low EMFs, many countries have adopted a regulatory framework based on prevention criteria. However, no evidence showing that such a relationship would exist has been found. Although the recommended exposure limits to EMFs are high when compared to usual EMFs values in domestic and work environments, it is noteworthy that those limits have decreased along the past decades based on prevention criteria.

Nowadays, with the development of the hybrid and electric vehicle (EV) technology, an evaluation of the electromagnetic environment inside these cars becomes necessary. EVs have an electric system of significant power, consisting of batteries, power converters and electric motors (besides all the connecting wires between them), usually located very close to the passengers. For example, it is a common practice to place the battery stack as far as possible from the bodywork, in order to minimize the risk of battery damage and its consequences in case of crash. This arrangement implies placing them just under the seats. This means that, during accelerations or deep regenerative braking, there might be currents of hundreds of amperes circulating a few centimetres away from the passengers.

The magnetic fields existing on-board can be of different frequencies depending on the devices which create them. Their values vary from the zero frequency of the DC cables to the several kHz of the harmonic components due to the inverter commutation.

As far as the authors are concerned, there are not many recent studies regarding EMFs and health issues in electric cars [4]–[6]. Although there are many papers which address the issue of EMFs created by power electronic devices, those studies are only made from the point of view of electromagnetic compatibility (EMC) and interference (EMI) [7]–[9].

In this paper, the magnetic field generated by an electronic converter is studied, modelled and evaluated, with the purpose of determining whether or not these devices could be hazardous to the passengers of an EV. A methodological analysis, based on a 3-D finite element analysis, is developed. This methodology, whose results have been validated with measurements, is applicable to any electronic converter within any electric system.

Section II is dedicated to the regulations concerning the recommended limits for public exposure to EMFs, and to review the studies present in the literature regarding both EMFs and vehicles. In Section III, a power electronics converter is modelled using FEA techniques, in order to determine the magnetic field values reached at a given distance of the device. Section IV is dedicated to the measurements taken in the real inverter during laboratory tests, which are compared to the simulation results in Section V. Some guidelines for vehicle design, which may prove useful to achieve a reduction of the magnetic field inside

TABLE I

REFERENCE LEVELS FOR GENERAL PUBLIC EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS

Frequency range	Electric field strenght E (kV m^{-1})	Magnetic field strenght H (A m^{-1})	Magnetic flux density B (T)
1 Hz-8 Hz	5	$3.2 \times 10^4/f^2$	$4 \times 10^{-2}/f^2$
8 Hz-25 Hz	5	$4 \times 10^3/f$	$5 \times 10^{-3}/f$
25 Hz-50 Hz	5	1.6×10^2	2×10^{-4}
50 Hz-400 Hz	250/f	1.6×10^2	2×10^{-4}
400 Hz-3 kHz	250/f	$6.4 \times 10^4/f$	$8 \times 10^{-2}/f$
3 kHz-10 MHz	0.083	21	27×10^{-5}

Notes:

-f is the frequency of the field in Hz.

-E, H and B in unperturbed rms values.

-In the range above 100 kHz, RF specific reference levels need to be considered additionally.

of an EV, are presented in Section VI. Finally, in Section VII some conclusions are established.

II. State of the Art

A. Recommended Exposure Limits to Electromagnetic Fields: ICNIRP Criteria

The most extended criteria for recommended exposure limit to EMFs were proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 1998 [10], and many European countries adopted these security limits. Ten years later, no new scientific evidence of any adverse effects had been found [11], reason why a review of the guidelines on limitation to exposure to High Frequency EMFs (HF, 100 kHz to 300 GHz) was considered unnecessary. Nevertheless, concerning Static EMFs and Extremely Low Frequency EMFs (ELF, 1 Hz to 100 kHz), special guidelines were published in 2009 [12] and 2010 [13], respectively, in an attempt to include the results of the main scientific publications during those ten years. The referred publications not only established recommended exposure limits to EMFs, but also included explanations concerning the ways these fields could affect human health.

Regarding the exposure limits to EMFs, different considerations arise depending on the person affected. Thus, there is an "occupational exposure", which is applied to those individuals who are exposed to EMFs as a result of performing their regular job activities. There is also a "general public exposure", which refers to the rest of the population.

Exposure limits for static magnetic fields are 400 mT for general public and 2 T for occupational [12], whereas the Earth's magnetic field ranges from 30 to 60 $\mu\mathrm{T}$, depending on the region on the Earth.

Concerning time-variant fields, the exposure limits to EMFs for "general public" are given in Table I [13].

It is noteworthy that these voluntary guidelines are not legally mandatory, and that they become legally binding only if a country incorporates them into its own legislation [14].

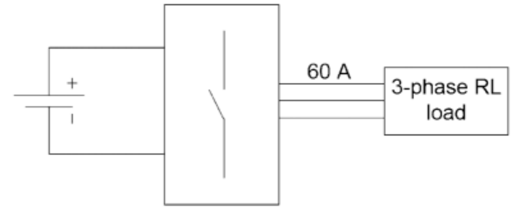


Fig. 1. General scheme of the simulated system.

B. Electromagnetic Fields: Previous Studies

Magnetic field measurement is not a new discipline. There are studies that attempt to evaluate theoretically the electromagnetic environment for different applications, comparing the results with measurements [15], [16]. These publications are mostly focused on problems concerning workers and industrial environments. Analyses of electromagnetic field levels in power lines [15] and substations [17] are the most common applications of EMFs measurement and evaluation.

Some publications concerning EMFs focus on the analysis of EMC and electromagnetic interference (EMI) [7]–[9]. One of the goals of [7] is to provide a tool to optimize the layout of motor drives from the point of view of EMFs. A similar line of work has been carried out in [18], evaluating and measuring the effectiveness of electromagnetic shielding in order to decrease the magnetic field.

Regarding general public, very little research has been published. These studies have mainly focused on matters such as urban environment and household appliances.

Concerning electric vehicles, some works have studied possible health issues for electric railway drivers and passengers [5], [19], and the possible hazards of EMFs for the general public in electric cars [4]–[6]. In all these studies the results were either inconclusive or far below the levels recommended by the ICNIRP.

III. Simulation Model

The study of the EMFs induced by a power electronics inverter began with the establishment of a 3-D finite element model. The simulated system is shown in Fig. 1. The finite element software used was Ansoft Maxwell 3D.

The modeled power converter is based on the SEMIKRON SKS 60F B6CI 35 V12 device with a maximum output current of 60 $\mathbf{A_{rms}}$, an input DC voltage of 650 V, and an output voltage of 400 $\mathbf{V_{rms}}$. The dimensions of the experimental inverter are $\mathbf{320 \times 249 \times 234\ mm^3}$, corresponding to a small converter with a power of 12 kW.

A. Introduction to the Finite Element Model

In order to have the best compromise between precision and effectiveness, just the most relevant parts of the inverter were modelled.

As the circulating currents are the only producers of magnetic field inside the device, the elements considered were the following:

— The two input DC wires coming from the batteries and connected to the semiconductors, represented by the red and black wires in Fig. 2.

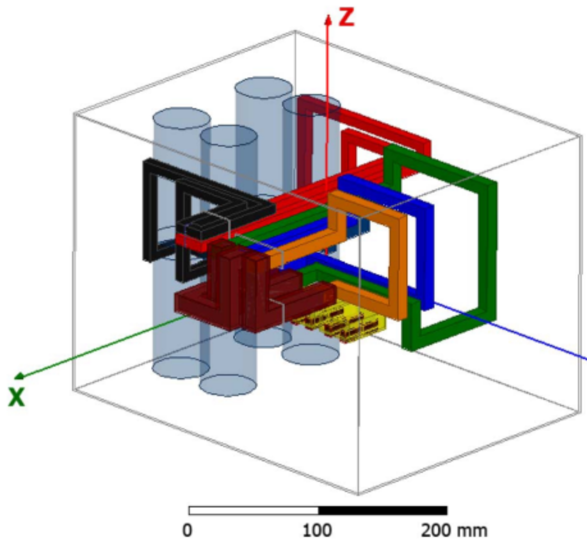


Fig. 2. 3-D finite element model of the converter.

— The semiconductors, responsible for the inversion of the DC current. They receive from the DC wires into the output AC current, by means of high frequency switching. These elements are inside the three yellow cases of Fig. 2, each one regrouping the semiconductors of one of the three AC phases.

— The three output AC wires, which connect the inverter to the electric motor. They are depicted in green, blue and orange in Fig. 2.

— The case of the inverter (transparent in Fig. 2). Built with a ferromagnetic steel (thickness: 1 mm, relative permeability in the linear region: 100), the case works as a magnetic shield, decreasing the value of the EMF outside the inverter.

The DC-link capacitors, painted on transparent grey in Fig. 2, were considered just to complete the graphic representation of the inverter. Their EMFs were expected to be almost inexistent, and therefore were not evaluated in this study.

In order to simplify the calculations, the following considerations were made concerning the geometry of the model.

Wires were modelled with square section instead of circular section to reduce the number of finite elements required for the simulations. The wires in the model and in the real inverter follow the same path (the loops shown in Fig. 2 are due to the presence of current sensors inside the Y+ face).

The finite element software used allows one value of current per closed circuit, forcing the creation of as many independent circuits as different currents. Two circuits were created for the DC side, three for the AC wires, and twelve for the semiconductors.

Since some connections were added to close the circuit loops in the model, which are not present in the real inverter, a perfect magnetic shield was placed around these connections in order to suppress the EMF created.

The semiconductors were modelled as wires of 1 cm length. A distance of 2 cm separates the IGBTs from the diodes, while the TOP and BOTTOM semiconductors of each phase are at 7 mm from each other. These electronic devices are set in the center of the inverter at more than 9 cm from the nearest face. All the semiconductors are close to each other, while being far from the sides of the inverter.

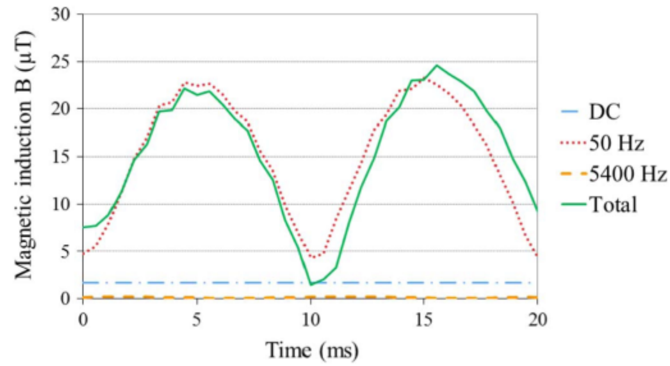


Fig. 3. FEM results showing the evolution over time of the magnitude of the magnetic induction at 20 cm of the Z+ face of the inverter.

A transient simulation was run with a resolution of 500 μs. The initial mesh of the model was configured by means of a magnetostatic simulation with adaptive meshing (the mesh is refined in each iteration). Mesh refinement operations were defined for the conductors and the regions surrounding the axes. Special parallelepiped areas were set up around each axis with a refined mesh to decrease the overall number of elements without affecting the accuracy of the results.

B. *Model Simplifications/Preliminary Conclusions*

Four simulations were performed with different currents circulating in the inverter, in order to assess the EMFs produced by each current at a given frequency. Therefore, each simulation dealt with only one specific current:

— The direct current in the input wires (116 A, DC).

— The low-frequency AC currents in the output wires (192 $\mathbf{A_{rms}}$, 100 Hz).

— The high frequency pulsed current in the semiconductors (136 $\mathbf{A_{rms}}$, 5.4 kHz).

— All the previous currents flowing at the same time, which is the normal operation of the converter.

Due to the high number of finite elements needed in the 3-D model, the magnetic fields around the converter were calculated only in four axes coming out from the centre of four sides of the inverter (namely X-, Y+, Y- and Z+), as presented in Fig. 2.

To decrease the number of elements without affecting the accuracy of the results, special volumetric regions were defined around each axis with a refined mesh.

The analysis of the data obtained from the first simulations, depicted in Fig. 3, led to conclusions and simplifications of the study. The magnetic induction obtained for the different cases of current considered shows that most of the magnetic field is generated by the low-frequency alternating current (AC component).

The magnitude of the magnetic induction produced by the DC cables is less than 10% of the total value induced when all the currents are present. The low field levels produced by the DC cables could be explained by the proximity of the cables, which cancel each other's field.

TABLE II
SUMMARY OF THE VALUES REACHED BY THE EMFS AT 20 cm OF THE INVERTER IN THE Z+ AXIS

	DC	AC	HF
Simulated values at 20 cm (rms)	1.69 μT	18 μT	0.37 μT
ICNIRP recommendation limits	200 mT	200 μT	27 μT

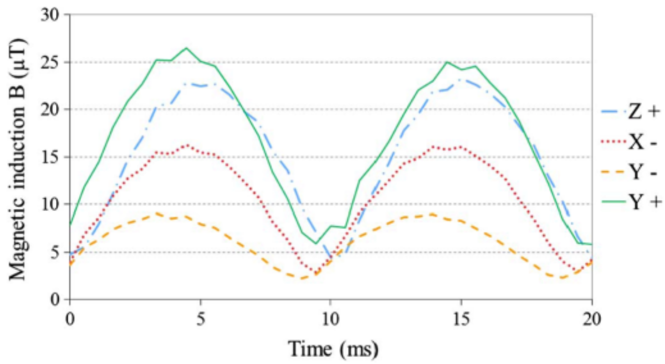


Fig. 4. FEM results showing the evolution over time of the magnitude of the magnetic induction at 20 cm of the faces X-, Y-, Y+ and Z+.

The magnetic induction generated by the semiconductors (HF) results even lower than the DC field. The maximum values do not reach 1 μT at 5 cm out of the inverter.

As Table II shows, the magnetic field closest to the recommended maximum values is the one induced by the AC component. Therefore, the only magnetic induction that will be considered in the following simulations will be the one induced by the low-frequency currents (100 Hz).

In order to get a more precise map of the magnetic fields induced by the inverter, a second set of simulations was carried out considering just the low-frequency alternating currents (AC) in four faces of the inverter: X-, Y-, Y+ and Z+. The purpose of this second set of simulations was to analyze the inductions coming out of each face of the device. The X+ face corresponds to the side of the device with the DC input and AC output connections. Given that the magnetic fields existing around this face would depend on the particular position of the wires in each EV, the analysis of this face was not considered in the study. The results are depicted in Fig. 4.

It is found that the directions that are most critical regarding magnetic field levels are Y+ and Z+, as expected given the spatial configuration of the field-generating elements of the inverter, depicted in Fig. 2. Namely, the $\mathbf{B_{rms}}$ values reached are 18 μT and 16 μT for the Y+ and Z+ axis respectively, against 11 μT and 6 μT for the X- and Y- axes.

The usual position of the inverter inside an EV, partly under the rear seats of the vehicle, would imply that the most exposed body parts would receive radiations coming out of the upper and one of the side faces of the device.

Considering that the most important EMFs came out from the upper face, Z+, and one of the side faces, Y+, it is concluded that the analysis of these two sides will be enough to establish the maximum levels of magnetic induction generated by the inverter.

TABLE III
MAGNETIC INDUCTION RESULTS (BOTH SIMULATION AND MEASUREMENTS) IN μT RMS, FOR CURRENTS OF 39 A AND 58 A (100 Hz), ON THE Y+ AND THE Z+ AXES

	Distance (cm)	Simulation		Measurements	
		39 A	58 A	39 A	58 A
Y+	10	8.55	13.10	8.43	12.64
	15	4.84	6.82	4.61	6.93
	20	3.09	4.33	3.04	4.26
	25	2.19	3.06	1.97	2.89
	30	1.65	2.30	1.44	2.07
Z+	10	6.85	9.75	7.37	10.60
	15	4.04	5.72	4.61	6.55
	20	2.33	3.28	2.95	4.09
	25	1.46	2.04	1.93	2.65
	30	0.99	1.37	1.38	1.89

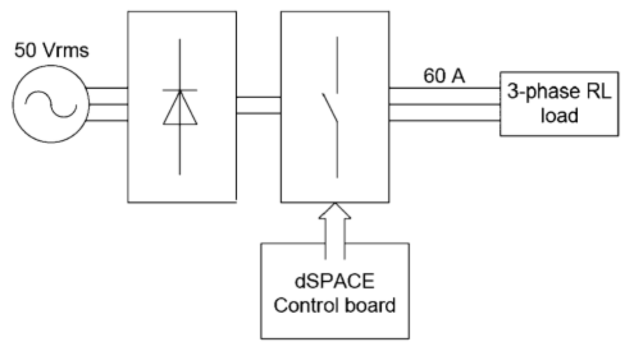


Fig. 5. Laboratory set up scheme.

C. Final Results

The final simulations were carried out on two faces of the inverter, corresponding to the Y+ and Z+ axis, and focused on the magnetic inductions produced by the low-frequency currents.

The results are shown in Table III. The five points included correspond to the distances where measurements were made with the real inverter in order to assess the validity of the finite element model.

IV. LABORATORY MEASUREMENTS

A. General Description

Laboratory measurements were taken on the same inverter that was previously analyzed in the finite elements study.

Two magnitudes were measured: continuous magnetic field, and alternate magnetic field. The measuring equipment consisted of two different devices: a continuous magnetic field meter (F.W. Bell 5170), and an alternate magnetic field meter (Combinova MFM10). These two devices were tested and calibrated by an authorized laboratory.

The laboratory set up used to perform the tests consisted of a controlled AC voltage source, a rectifier, the tested inverter, and a three-phase balanced RL load, as show in Fig. 5. The inverter was controlled through a dSPACE control platform, which was also used to take voltage and current measurements. The control

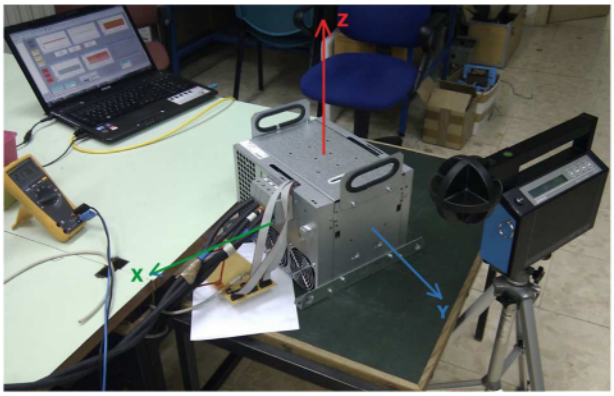
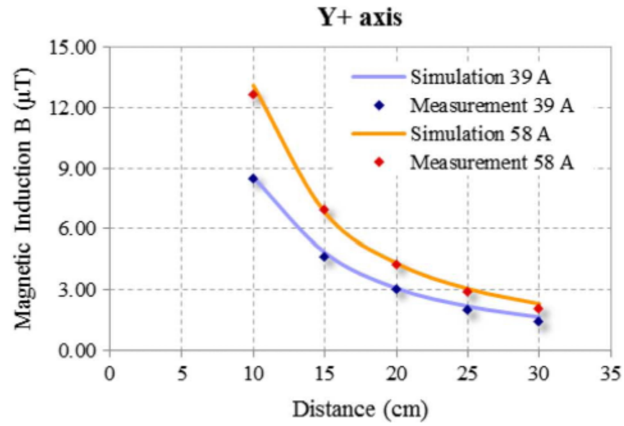
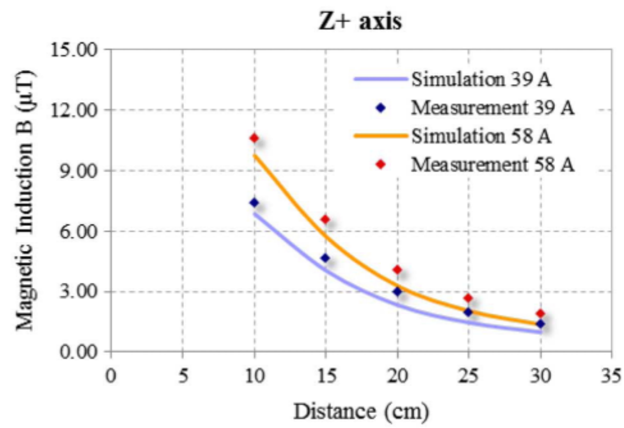


Fig. 6. Test bench for the measurements of the magnetic field coming out of the inverter.



(a)



(b)

Fig. 7. FEM simulation and measurement results, for both 39 and 58 A, for (a) the Y+ axis and (b) the Z+ axis.

strategy applied to the inverter consisted in an open loop three-phase PWM voltage control [20].

As can be seen in Fig. 6, special care was taken in order to place all the control and electronic devices, as well as their connections, far away from the area where the magnetic measurements were taken, that is, around the inverter.

B. Measurement Procedure

Measurements were taken considering different distances to the surface of the inverter and different working points of the device. Only two axes were taken into account, Y+ and Z+, given that they were the most critical, as explained in the previous section.

Each measurement has two associated parameters: distance to the corresponding surface of the inverter, and AC current (amplitude). The measurements were performed using two different current values (39 A and 58 A) and at five different distances from the inverter surface (see Table III). Each current distance combination was measured three times, resulting in a total of 60 measurements for each axis.

Measurements were taken by placing the field meters in the corresponding axis by means of a tripod.

A small offset was subtracted to the measured values in order to correct the background residual magnetic field. Similarly, a position-dependent calibration factor was applied to the measurements in order to compensate both the spatial averaging due to the size of the sensors and the reduced coupling that exists when measuring a local source.

C. Measurement Results

DC field values were far below the Earth's magnetic field, thus these measurements were considered irrelevant and were therefore eliminated from the analysis.

As for the AC field, Table III shows the average values of all the measurements taken.

V. Evaluation of the Measurements

A. Comparison with the Simulation Results

Fig. 7 shows both the simulated and the measured values of the AC field for the two current levels, and for both the Y+ axis [Fig. 7(a)] and the Z+ axis [Fig. 7(b)]. The agreement between simulations and measurements is very good, the largest deviation being less than 1 μ**T**. Therefore, the proposed simulation methodology was considered valid to make an accurate determination of the magnetic field environment around the inverter under other working conditions. Moreover, the same methodology could be applicable to other electronic converters in other applications.

B. Maximum Field Values Achievable Inside an EV

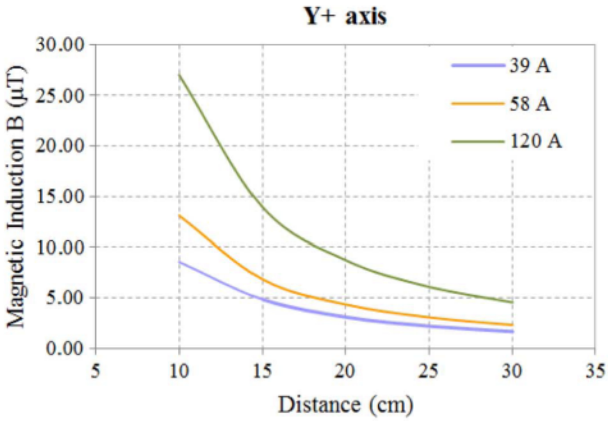
Once the accuracy of the finite element model was assessed, it was possible to simulate the EMFs coming out of the inverter with very high currents. This working point would correspond, for example, to an instant of strong acceleration or deep regenerative braking of the vehicle.

In this case, the current considered is the maximum transient current allowed by the inverter, 120 $\mathbf{A_{rms}}$ (100 Hz). Once more, the EMFs evaluated were those radiated by the Y+ and Z+ faces.

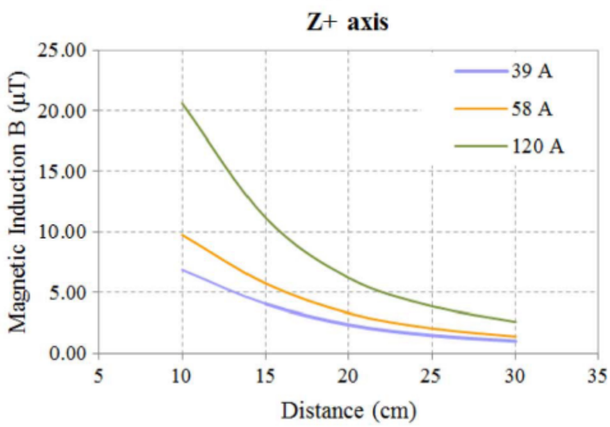
The results of these simulations are depicted in Fig. 8, along with those from the previous cases for comparison purposes.

C. Comparison With the Standard Limits

In this section, the maximum magnetic field values generated by the inverter inside an EV will be compared to the recommended limits published by the ICNIRP [13].



(a)



(b)

Fig. 8. FEM simulation results for current values of 39 A, 58 A and 120 A in the axes (a) Y+ and (b) Z+.

It is important to note that those recommended limits should be applied to the total field achieved in the interior of the EV and not only to the field generated by the inverter. The contribution of the other field-generating devices inside the vehicle must be taken into account in order to determine whether the field values may be hazardous or not [6].

In order to establish a comparison, it is considered that the inverter is placed inside the vehicle so that the closest passenger will be at 20 cm in the Z+ direction (worst-case scenario). The current in the inverter is set at the maximum, 120 $\mathbf{A_{rms}}$, so the magnetic field generated is also maximum.

Fig. 9 shows the simulated rms values of the DC, AC (100 Hz) and HF (5 kHz) magnetics fields at 20 cm of the inverter in the Z+ axis, in percentage terms, 100% being the value corresponding to the recommended limit of the ICNIRP (400 mT for DC, 200 μT for AC, and 27 μT for HF).

D. Comparison With Usual Field Exposure

The average residential power-frequency magnetic fields in homes are about 0.07 μT (50 Hz) in Europe and 0.11 μT (60 Hz) in North America. In the vicinity of certain electric appliances, the instantaneous values of magnetic field may reach some dozens of μT. In the surroundings of power lines, magnetic fields easily grow over 20 μT [3].

Consequently, the magnetic field values that could be generated by the electronic converter of an electric vehicle are a few times higher than those to which general public could usually be exposed to. This should be taken into account for future increases of the power level of EV drives.

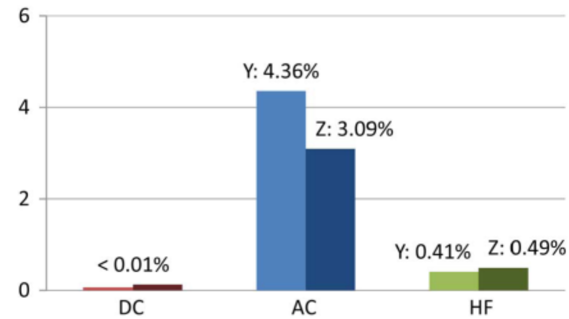


Fig. 9. Magnetic field values at a distance of 20 cm from the inverter in the Y+ and Z+ axes, in percentage with respect to the ICNIRP recommended limits, for a current of 120 Arms.

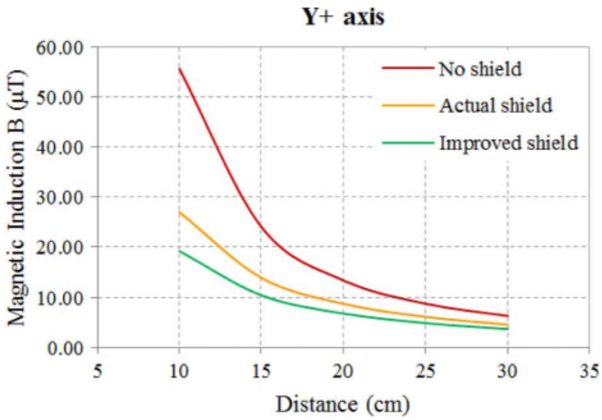
VI. Alternatives for Magnetic Shielding

A. Design Recommendations to Reduce Non-Ionizing Radiation On-Board

Although the field values created by the inverter of the studied vehicle are low, it must be noted that there are EVs of many different types (i.e., electric buses, competition cars, etc.), with different designs and power levels. Consequently, the issue of the EMFs in the interior of EVs should be kept under strict surveillance.

In this sense, some guidelines to reduce EMFs inside an EV are now presented. It must be considered that they are recommendations of purely electrical nature, and therefore they may not be applicable when considering other factors. These recommendations are based in an "As Low As Reasonably Achievable" (ALARA) criterion. In other words, the aim is to keep the exposures as low as reasonably possible with the technical and economical means available. The ALARA criterion allows the implementation of protection strategies at an acceptable cost, and it is preferably applied during the first stages of the design process of the EV and its components.

1) Wires of the same type should be as close as possible of each other: Both DC wires must be taped together; similarly, the three phase AC wires must be taped together, preferably in triangular disposition.
2) Wires should be as short as possible, except when this involves bringing them closer to the passengers.
3) The battery stack, the electronic converters and the motor should be away from the passengers. Batteries are usually placed just under the seats, in order to minimize risks in case of crash. However, this involves bringing them closer to the passengers. A compromise should be reached.
4) Similarly, the batteries could be redesigned in order to allow terminals to be placed at the bottom. This would increase the distance from the stack connections to the passengers in a value equal to the height of the batteries.
5) The higher the voltages, the lower the currents and the magnetic field, but the higher the electric field. However,



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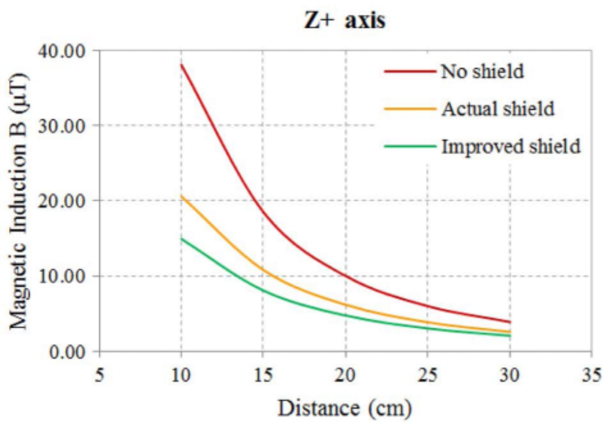

(b)

Fig. 10. FEM results showing the magnetic field values for 120 A with different magnetic shields for the axes (a) Y+ and (b) Z+.

high on-board voltages may be hazardous in case of crash, so once again a compromise would be necessary.

All the aforementioned guidelines involve neither a drastic change in the EV design nor an increase in its weight or cost. If further actions were necessary in order to reduce the EMF inside the car, these additional recommendations may prove helpful:

6) In-wheel motor technology allows the devices inside an EV to be distributed in a much more flexible way. The space reserved for the conventional motor could be occupied by the battery stack instead, which would mean that no field-generating devices would be placed under the seats.
7) A magnetic shield could be placed around the devices responsible for the magnetic field in the interior of the car.

B. *Magnetic Shielding of the Inverter*

To conclude the study, a series of simulations were carried out to test the importance of the material used to build the case of the inverter.

In order to decrease the magnetic induction outside the device's case, ferromagnetic materials can be used to create a magnetic shield. Three different alternatives were analyzed:

- An inverter with a plastic case of polyethylene, which has no magnetic properties and shields no magnetic induction (relative permeability: 1).
- The ferromagnetic material corresponding to the real inverter (relative permeability in the linear region: 100).
- An inverter with an improved ferromagnetic material, (relative permeability in the linear region: 2000).

The results obtained, shown in Fig. 10, underlined the role of the magnetic shield created by the ferromagnetic material of the case of the converter. The values attained with the real magnetic shield were twice lower than without shield, while an improved ferromagnetic material could achieve an extra reduction of 25%.

In cases of high levels of EMFs, the setting of good magnetic shields using ferromagnetic materials with a high relative permeability could be an efficient way of decreasing the exposure.

VII. Conclusion

So far, it has been rare to find situations in which the general public daily shared living space with an electric system of significant power. However, electric vehicles involve exactly that. In this paper, a method to evaluate the magnetic field generated by an inverter from the point of view of human health has been proposed. This methodology may also be of interest regarding electromagnetic compatibility studies, and even for other applications. A finite elements model has been developed and laboratory measurements have been taken in order to validate the model. These results have also been compared with current recommendations concerning exposure limitation to electromagnetic fields, finding field levels well below the limits. Finally, the proposed model, once validated, has been used to estimate the maximum magnetic field achievable inside an electric vehicle carrying the tested inverter, and some general design guidelines to minimize electromagnetic field exposure inside electric cars, including magnetic shielding, have been proposed, for the cases in which a reduction may be needed.

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